Merits and Limitations of Helium in the Optimization of Spacecraft Cabin Atmosphere Composition and Pressure

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Abstract

All current extra-vehicular (EVA) operations utilize spacesuit pressures that are much lower than pressures assigned to the nominal spacecraft cabin in order to enhance astronaut dexterity through the improved spacesuit flexibility attainable only at relatively low distention pressures. Decompression sickness risk accompanies EVA which involve such significant spacecraft cabin to spacesuit pressure differentials (delta P). This concept presentation and demonstration experiment offer general strategies which could lower decompression sickness risk during EVA. The combined tactics of adding a highly diffusible inert gas (helium) as a cabin atmosphere component and lowering nominal spacecraft cabin pressure slightly below 1 atm act in synergy to theoretically reduce the tissue bubble formation consequences termed decompression sickness possibly associated with current EVA procedures. Further studies and experiments are proposed to ascertain the feasibility of using a novel mixed gas atmosphere in the spacecraft cabin to reduce or eliminate the lengthy prebreathing protocol required of astronauts today, before they embark on EVA missions.

Introduction

In the early phases of the Cold War era space race between the United States and Russia, extra-vehicular activity (EVA) quickly became a prized accomplishment to demonstrate technical prowess and empower the capabilities of manned space missions. Theories and sketches of the great 20th century Russian space pioneer, Konstantin Tsiolkovsky, presaged the important role commanded by EVA to enable space exploration. [1] Ultimately, Russia led mankind's every venture into space, even in the spacewalk arena.

EVA success was preceded by arduous engineering efforts to surmount space environment hazards. Nearly every spacecraft function must be replicated in miniature by EVA spacesuits with purposeful laminated construction to address challenges which include extreme vacuum, wide thermal variation, intense radiation, surface charging, and micrometeoroid impacts. Spacesuit utility demands protective measures balanced against

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mobility requirements and packaged for endurance, reliability, and comfort. Early aviation high-altitude pressure suit designs progressed through a circuitous evolutionary path to finally result in the operational EVA spacesuits for lunar exploration and International Space Station missions. [2]

The great conflict between operational requirements of the spacecraft cabin and the spacesuit became manifest even during the first spacewalk (March 18, 1965) by Alexei Leonov aboard the Russian spacecraft Voskhod 2. Spacesuit over-distention and mobility restriction dangerously crippled the cosmonaut's return to the spacecraft. Progressive bulging of the spacesuit exposed to the vacuum environment exceeded accommodation by the hatch and Leonov re-entered the spacecraft only through heroic physical efforts combined with risky spacesuit pressure level decreases. [3] Spacesuit evolution to current operational models yielded vast safety, reliability, and mobility improvements; yet, even today, the soft spacesuit components (especially gloves) required for dexterity attain useful mobility only at low pressures (3.7-4.3 psi). [4] This rarified spacesuit atmosphere demands a 100% oxygen concentration to support cosmonaut/astronaut physiology.

Early U.S. spacecraft cabin designs incorporated a low atmosphere pressure (5 psi) for structural concerns despite the attendant necessary risk of a 100% oxygen concentration. [5]Increasingly sophisticated modern spacecraft possess sufficient structural mass to permit a 21% oxygen concentration at sea-level pressure with allowance for inert gas components that enhance cabin safety and comfort. [5] Ironically, the general tendency toward sea-level cabin pressure in U.S. spacecraft and the consistent use of near sea-level cabin pressure in Russian spacecraft poses a significant risk of decompression sickness to crew involved in EVA using relatively low pressure spacesuits. Indeed, the Voskhod 2 mission initiated mankind's first spacewalk from a sea-level cabin pressure of Earth atmosphere composition, thus foreshadowing the technical challenges of current spacewalks requiring a preparatory 100% oxygen pre-breathing period of 1-4 hours (U.S. programs). [5]

Merits and Limitations of Helium

The risk of decompression sickness arises from ANY inert gas atmosphere component (nitrogen, helium, etc) and that risk generally intensifies as molecular weight of the inert gas component increases. [6] A relatively high molecular weight gas such as nitrogen (28 kg/kmol) diffuses much slower than the lightest physiologically inert gases such as helium (4 kg/kmol) or hydrogen (2 kg/kmol). Hydrogen would never be considered as a spacecraft cabin atmosphere component due to its extreme flammability; however, the noble gas, helium, confers both the physiological attributes which avert decompression sickness and the chemical inertness which enhances fire suppression. Additionally, the low blood and lipid solubility of helium further facilitate its desaturation without bubble formation in body tissues.

Despite the fortuitous properties of helium as an inert gas component, several significant technological challenges accompany its use in spacecraft. As a highly diffusible gas, helium readily penetrates standard seals (even air-tight seals). Advances in nanotechnology may offer promise in the design of coating materials and seals to better contain helium. Furthermore, the high frequency voice distortion associated with helium's low density/viscosity creates a formidable impediment to crew speech recognition and communications. Also, the extremely high thermal conductivity of helium demands tight control of cabin temperature for crew comfort in a shirtsleeve environment. [7]

Introduction of helium as a third gas in the spacecraft atmosphere has been suggested to increase the complexity of monitoring and handling the complex atmospheric components, including plumbing, but premixed gases such as Heliox have not shown any insurmountable problems in system design or during operations in deep sea diving.

Proposal for Mixed Gas Spacecraft Atmosphere

Maximal realization of helium's beneficial effects while blunting its disadvantages may be achievable in a multi-gas spacecraft cabin atmosphere using helium to significantly dilute the nitrogen inert gas component. Thus, the concept of multiple inert gas components explores the potential to increase mission safety and efficiency by reducing decompression sickness risk and minimizing oxygen pre-breathe requirements for EVA. Observing the physiologic requirement for 160 mmHg oxygen partial pressure balanced against the fire safety precaution of a 30% maximal cabin oxygen concentration would bound the minimum absolute cabin pressure at 533 mmHg. [8] Minimization of the difference between spacecraft cabin pressure and spacesuit pressure lowers decompression sickness risk by lessening the pressure transitions (delta P) which encourage bubble formation in body tissues. The compromise between the maximum allowable Oxygen concentration and the lowest cabin to spacesuit pressure differential could favor an intermediate absolute cabin pressure such as 650 mmHg with composition:

Component	Partial Pressure		Concentration (%)
	mmHg	psi	
Oxygen	160.0	3.09	24.6
Nitrogen	239.3	4.62	36.8
Helium	239.3	4.62	36.8
Water vapor*	11.4	0.22	1.8
TOTALS	650	12.6	100

*Assumption: 58% relative humidity at 22 degrees Celsius

Assuming blood/tissue saturation with the inert gas components, expectable rapid desaturation of helium would leave a much less problematic nitrogen partial pressure to decline from body tissues during oxygen pre-breathe procedures. Presumably, the undesirable helium effects such as voice distortion and body heat loss would decrease commensurate with helium dilution by nitrogen while in the spacecraft cabin.

Theoretical Consideration

A theoretical concern regards decompression sickness induced by initial exposure of the crew to reduced cabin pressure and the novel atmosphere after launch. The rapidity of the ambient pressure reduction combined with the phenomenon of isobaric counterdiffusion could risk tissue bubble formation until the body tissues have achieved the new inert gas component equilibriums in the novel spacecraft atmosphere. Isobaric counterdiffusion describes the opposite movement of inert gas components caused by breathing an inert gas mixture which differs from the body tissue inert gas saturation mixture. [9] Specifically, the Earth atmosphere creates blood/tissue nitrogen saturation at 600.4 mmHg (79% nitrogen at 1 atm) and, without prior de-nitrogenation, the inhalation of a helium component would cause a relatively slow partial de-nitrogenation to the new nitrogen partial pressure accompanied by a relatively fast helium saturation to the helium partial pressure. Because helium diffuses into body tissues faster than nitrogen diffuses out of those body tissues, a transitional body tissue gas tension supersaturation above ambient pressure theoretically precedes equilibrium at ambient pressure. This isobaric counterdiffusion effect becomes most pronounced with huge pressures experienced by deep sea divers during gas switches at decompression stops. Medical use of Heliox (80% helium/20% oxygen) at 1 atm on the Earth surface does not reportedly demonstrate the problem of isobaric counterdiffusion – presumably due to its reduced effect in a stable, relatively low pressure (1 atm) environment. [10] Nonetheless, the pressure transition to a new lower ambient pressure plus the inhalation of a new inert gas component (helium) could unmask the potentially deadly effect of isobaric counterdiffusion in astronauts initially equilibrating to a novel atmosphere – thus, 100% oxygen pre-breathing and de-nitrogenation precautions should precede the launch and/or the novel atmosphere transition could occur gradually (for example, over a 24 hour period after launch). After safe initiation to the novel spacecraft atmosphere, the isobaric counterdiffusion phenomenon will no longer occur during a mission involving low pressure spacesuit EVA because transitions into a 100% oxygen atmosphere will only lower tissue inert gas saturation and return to the spacecraft cabin atmosphere will only allow tissue inert gas saturation levels to gradually approach the ambient partial pressure values.

While the precise selection of an optimal spacecraft cabin atmosphere composition and pressure requires mission-specific criteria and evaluation, this concept advocates consideration of helium as an inert gas component in spacecraft cabins supporting EVA in relatively low pressure spacesuits. Furthermore, the proposed concept utilizes spacecraft cabin pressures slightly below sea-level to minimize the pressure differential between the cabin and operational spacesuits. The objective of these strategies is to minimize the risk of decompression sickness and minimize the oxygen pre-breathing requirements associated with EVA.

The Rodent Experiment

A small experiment setup using rodents (mice) to verify any directly observable deleterious effects is presented (Figure 1). The rodent crew gradually transitioned over a 30 minute period to a novel atmosphere with partial substitution of helium for nitrogen as an inert gas component. Composition of this novel atmosphere mimicked the proposed spacecraft cabin atmosphere detailed on page 3 but utilized a total pressure of 1 atm to facilitate application of a simplified oxygen replenishment system driven by ambient pressure. Ambient atmospheric pressure initiated crew cabin oxygen replenishment by acting upon the plungers of 100 ml ground glass syringes (bank of 5) filled with 100% oxygen and maintained on a 22 degree tilt table calibrated for zero plunger resistance.

The oxygen replenishment system was isolated from the crew cabin volume (6 liters) by a 0.5 cm water pressure seal. Carbon dioxide was scrubbed from the crew cabin using forced ventilation through Sodasorb (100 g) layered with activated charcoal for atmosphere purification. Cabin condition monitoring included hourly measurements of temperature, pressure, humidity, oxygen level and carbon dioxide level. The crew cabin atmosphere composition was maintained as follows:

Component	Partial Pressure mmHg	Partial Pressure psi	Concentration (%)
Oxygen	160	3.09	21.0
Nitrogen	294	5.69	38.7
Helium	294	5.69	38.7
Water vapor	12	0.23	1.6
TOTALS	760	14.7	100

Within the confines of the metabolic isolation chamber meant to simulate a spacecraft cabin at 1 atm, two mice were successfully accommodated to the novel atmosphere for a 29 hour monitored period during which they demonstrated normal activity and feeding behavior without overt signs of impairment or distress.

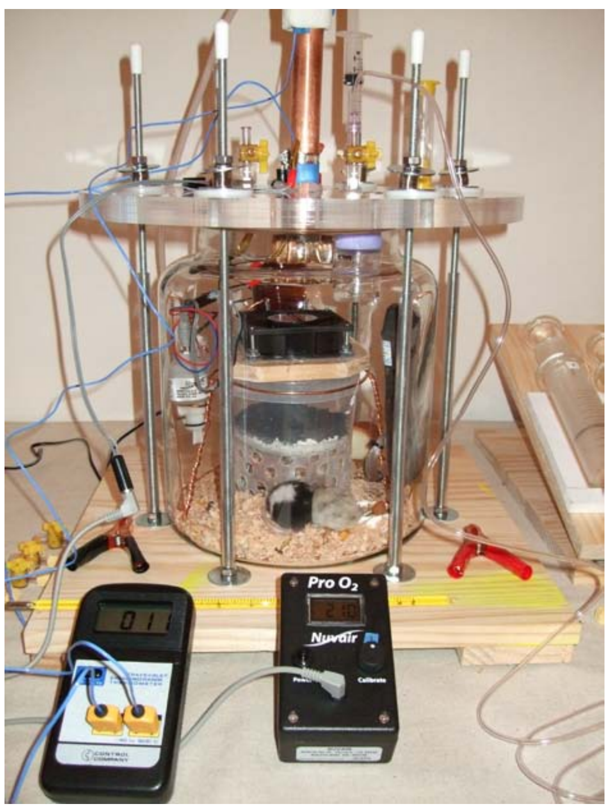

Figure 1. Metabolic isolation chamber for rodent observational tests in the novel atmosphere

Proposal for Further Studies

Scientific verification of the decompression sickness risk and the possible benefit of a novel atmosphere in lowering that risk could be studied in a much more elaborate and definitive experiment comparing the incidence of venous bubble formation in animal populations experiencing scheduled drastic pressure reductions from the standard Earth atmosphere and the novel atmosphere. Continuous ultrasonic (Doppler) monitoring of gas emboli formation in a major venous channel (femoral vein) could detect any significant difference in decompression sickness risk occurring in the studied animal populations. The animal (e.g. rat) subjects would require surgical implantation of miniature Doppler probes and radio transmitters in order to generate continuous data during normal activity. If a significantly lowered incidence of venous gas emboli can be demonstrated for the novel atmosphere, then that novel atmosphere should be considered for spacecraft cabins supporting EVA in low pressure spacesuits until the future development and implementation of hard spacesuits operating at nominal spacecraft cabin pressure.

The merits derived from Doppler determinations of venous gas emboli in animals experiencing wide atmosphere composition and pressure transitions would include an estimate of decompression sickness risk for astronauts subjected to similar conditions during EVA operations and an evaluation of the potential safety benefit associated with using a novel atmosphere. A limitation inherent to studies of decompression sickness risk is the common occurrence of asymptomatic yet detectable microemboli in subjects tolerating significant ambient pressure changes. [11] Nonetheless, the incidence and severity of detectable microemboli remains the best predictive test of decompression sickness risk. [12] Effective minimization of decompression sickness risk typically involves strategies found to inhibit the production and growth of microemboli before the occurrence of physical symptoms such as dyspnea, joint pain, nausea, disorientation, and neurological deficits.

Three areas offer promise for further exploration of mixed gas atmospheres for manned spacecraft application:

1. Animal studies as proposed above are the first in a series of experiments to validate the viability of introducing mixed gas atmosphere in spacecraft.

2. Hyperbaric medicine, where patients are subjected to higher than ambient atmospheric pressures to combat a variety of disorders inside hyperbaric chambers, is a rapidly evolving field in modern medicine.[13] It may be possible to conduct some critical experiments associated with mixed gas atmospheres in hypobaric conditions using the same chamber and infrastructure. If successful results are achieved, then we could proceed to the next level in space qualification.

3. Finally, we propose that a dedicated node or module on ISS be outfitted with proposed mixed gas constitution for a period of time to ascertain that there are no other deleterious physiological effects on crew or space system degradation associated with such an atmospheric makeup.

Conclusion

Further development of EVA spacesuits undoubtedly favors an Earth atmosphere composition and pressure for both the spacecraft cabin and the spacesuit in order to minimize risks of fire and decompression sickness. This seamless atmosphere transition from spacecraft cabin to spacesuit requires a constant volume hard spacesuit which allows adequate mobility despite the relatively high spacesuit pressure. Incorporation of the hard spacesuit into future missions and spacecraft will require spacious accommodation of this relatively bulky and unyielding garment in addition to refinements in mobility and dexterity according to mission-specific goals.

The redoubtable soft spacesuit possesses an impressive service record spanning the history of space exploration. Despite the fire hazard of its 100% oxygen atmosphere and the mobility restrictions of this cumbersome garment, the soft spacesuit offers validated operational performance for a wide variety of space missions. Budgetary constraints may well restrict the near-term evolution of soft spacesuits into a hard spacesuit with an Earth atmosphere environment. The utility of current soft spacesuits could benefit from safety enhancements applied to critical issues such as decompression sickness. The incorporation of a novel atmosphere with a helium component into spacecraft cabins supporting soft EVA spacesuits could increase safety margins by lowering decompression sickness risk and increase efficiency by minimizing or eliminating oxygen pre-breathing requirements in use today.

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http://denecs.usc.edu/hosted/ASTE/TeamProject20093/

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